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Palisades, New York

Technical Report on Seismology No. 24

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MICROSEISM GROUND MOTION AT PALISADES AND WESTON

by

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The research reported in this document was supported by Contract N6-onr-27133 with the Office of Naval Research of the United States Navy Department and Contract AF19(122)441 with the Geophysical Research Division of the Air Force Cambridge Research Center. (Report No. 22).

CU 10 53-onr 27133 Geol.
CU 30 53-AF 19 (122) 441 Geol.

January 1953

ABSTRACT

An analysis of microseism ground motion at Palisades and Weston is made on the basis of both statistical and individual wave studies. Data from three-component seismographs are utilized for the study of six microseism storms. The results of both methods of ground motion analysis show that the microseisms studied for Palisades and Weston are either pure Rayleigh waves or combinations of Rayleigh waves approaching from different directions. The study also tends to support earlier findings of Lee that a relationship seems to exist between certain microseism parameters and local geology. The use of the data to determine wave approach directions on the assumption of Rayleigh waves supports earlier reports of refraction at the continental borders, and gives further evidence for the existence of a microseism discontinuity at the margin of the continent in the vicinity of Long Island.

INTRODUCTION

Since the earliest discussion and naming of microseisms by Bertelli (1) much attention has been given to the still-unsettled problem of origin of the 2-10 sec microseisms. However, studies of microseism ground motion lagged behind long-range statistical studies involved in correlation with factors of possible origin; e.g., Zoeppritz (2), Geussenhainer (3), and Mendel (4). These, and other early studies did serve to show striking variations among the three components at a given station and among different stations.

With the wider application of the three-component seismograph to the study of microseisms, which began in the 1930s, Lee (5,6,7,8), Leet (9), Wadati and Masuda (10) and Archer (11), and more recently Ramirez (12), Wilson (13), Leet (14, 15), Kishinouye and Ikegami (16), d'Henry (17), and Ikegami and Kishenouye (18, 19)] a more complete picture of total ground motion has been obtained for each of the stations studied. Somewhat divergent observations have resulted from these investigations so that microseisms have been described for some localities as essentially Rayleigh-wave type motion and for others as a combination of Rayleigh- and Love-wave type motions. Since very few attempts at a complete study of microseism ground motion have been published for North American stations it is hoped that this work will add valuable data to the problem of the nature of microseisms, especially in view of the differences in current observations.

The seismograms used in this study were from instruments with the following characteristics:

Palisades - N and E, T_0=12 and 13 respectively, T_g=13
Z, T_0=11, T_g=14

Weston - long-period Benioff, N,E,Z, T_0=1, T_g=60.

Calibration curves are available for the Palisades instruments. Long use of these curves in earthquake studies have indicated their reliability for waves of 20 sec or longer. To check the reliability of the data on instrumental response for shorter-period waves, Rayleigh waves (R_g) for the Alaskan shock of May 26, 1950 were measured on Palisades records. These waves, with periods of about 8.5 to 12 seconds are close to the microseism period range. These waves showed orbital motions typical of Rayleigh waves and also showed good horizontal polarity which indicated the direction of the epicenter to within a few degrees. The longer axes of the orbits showed pronounced inclination in the direction of propagation as is shown by those of the microseisms to be given later. It is concluded that the instrumental response is also known with sufficient reliability in the microseism range of periods, in the case of the Palisades instruments. The Weston data was obtained from matched Benioffs for which no calibration curves were available. However the uniformity of the results to be given later indicates that differences from expected phase response and magnification among the components are within such sufficiently narrow limits as to have no serious effect on the results and conclusions.

A total of six microseism storms were selected for investigation with Weston records available for one of these. The storms were selected so as to include a wide range of periods (about 3 to 8 sec) and for meteorological conditions that appeared simple; in addition to cases that were close to the time of initial calibration of the instruments.

STATISTICAL ANALYSIS OF PHASE RELATIONSHIPS AMONG THE THREE COMPONENTS

The procedure used here is based upon that described by Lee (8). All measurements and calculations were made every six hours during the six microseism storms, with phase measurements being recorded for one-hundred waves in close sequence. Continuous measurements were made at the minute marks and at ten-sec intervals until one-hundred waves identifiable on all components were included. This covered about thirty minutes. According to the system of Lee and others, a wave cycle is divided into sixteen parts with the phase angles represented by the points of division being given numbers from "0" to "15" in the manner shown in Fig. 1. In reliability measurements it was found that the precision of phase readings was within one unit. To compare the ground motion shown by each component, the phase differences, Z-E, Z-N and N-E were determined for each one-hundred waves measured. Phase differences of instrumental origin were determined to be about 20 degrees for Z-E and Z-N, and 5 degrees for N-E for the microseism period studied. The final results were corrected for these errors in a manner given later.

The frequency of occurrence of each of the sixteen possible phase differences was determined and three frequency distributions (corresponding to Z-E, Z-N and N-E) were obtained. The frequency values in these distributions were smoothed by overlapping weighted groups of five values as given in the formula

$$F'_n = \frac{F_{n-2} + 2F_{n-1} + 3F_n + 2F_{n+1} + F_{n+2}}{9}$$

where F'_n is the smoothed frequency and
F_n is the number of observations of any phase difference, (n).

Table I gives smoothed percentage-frequency distributions of phase differences for the microseism storms studied. To indicate the order of period involved, the average period of only the vertical, T_z, is given for each case since no significant or constant differences occurred among the components. Wilson (13) however, found that the periods of the horizontals at Berkeley were consistently one-half sec longer than those of the vertical.

Table I shows a preponderance of phase difference distributions at certain values, as shown by the underscoring. Table II gives a numerical summary of the most commonly occurring phase differences shown by underscoring in Table I. For the N-E distribution, 0 and 180 degrees are most frequent, although Table I shows that all possible phase differences are represented. The combined results for Z-N and Z-E at Palisades show most frequent occurrence at either 135 or 315 degrees. For Weston most frequent occurrence for Z-N and Z-E is at either 112½ or 202½ degrees, with all possible phase differences again being represented in Table I.

Considering the retrograde elliptic movement of Rayleigh waves and the fact that an up-trace movement on the seismograms used corresponds to ground motions that are east, north or up, the phase differences between the vertical and the horizontals should be 90 or 270 degrees depending on the direction of wave approach. Further, the differences between north-south and east-west components should be either 0 to 180 degrees, again depending on the direction of approach.

Clearly the observed phase differences for the horizontals (N-E in the tables) are in good agreement with Rayleigh wave theory, but are 45 and 22½ degrees too large for the differences between vertical and horizontals (Z-N, Z-E) at Palisades and Weston respectively. However, if the instrumental correction of about 20 degrees given by calibrations) is made for the Palisades results they would then match those for Weston. (No correction is made for the matched Weston components). This leaves for both stations a residual difference between observed and theoretical values for Z-N and Z-E of about 25 degrees, which was also found by Lee (8). Recent theoretical work of Caloi (20) may apply as an approximation to a layered crust. Caloi showed that the axes of the elliptic particle paths in Rayleigh wave motion should be inclined in an infinite, isotropic, visco-elastic medium which is comparable to the average rock of the earth's crust. Presumably the amount of inclination will be affected by both layering and rock type. Dobrin (21) and Misler (22) have recently reported on inclinations of Rayleigh wave orbits produced in explosion seismology.

Assuming that the observed microseisms approached from the coast (east) and generally from the direction of the most obvious meteorological disturbances, the observed phase differences indicate retrograde orbital motion. It is important to note that any mechanism causing ground particles to move in elliptic paths would appear to explain the observed phase differences, but might not produce retrograde rotation, as observed here. Gutenberg (23) for example has shown that a combination of incident and reflected SV waves at the earth's surface could produce an elliptic motion at epicentral distances of 30 to 2,000 km, which includes the distances of most atmospheric disturbances associated with microseism storms.

STATISTICAL ANALYSIS OF AMPLITUDE RELATIONSHIPS AMONG THE THREE COMPONENTS

During the intervals in which phase measurements were made, the amplitude and period of the largest wave in each minute was also recorded. For each of the components the mean amplitudes, $\bar{X}_E$, $\bar{X}_N$ and $\bar{X}_Z$ were computed at each observation time of about 30 minutes duration. From this, the mean horizontal amplitude,

$$\bar{X}_H = 1\ (\bar{X}_E^2 + \bar{X}_N^2)^{\frac{1}{2}}$$

was computed. The ratio of the mean horizontal to the mean vertical amplitude ($\bar{X}_H/\bar{X}_Z$), and also the ratio of the horizontals $\bar{X}_E/\bar{X}_N$ were determined.

In Table III note that Weston amplitudes are given as trace amplitudes (magnification curves were not available and no correction was considered necessary), whereas for Palisades ground motion amplitudes are given. Ground amplitude calculations are based on the assumption of continuous sinusoidal waves. Although this is inadequate, the results for a particular instrument type would be affected in a similar way for a given wave form. Since this study essentially considers amplitude ratios, the above considerations can be neglected.

Although the periods and ground amplitudes for Palisades appear to be generally proportional during the progress of any particular microseism storm given here, they are unrelated when the data for all the storms are considered together.

To consider the ratio X_E / X_N for both stations, it is noted that these values are generally unrelated to period. This would be expected on the basis of Rayleigh wave theory, where this ratio is a function of the direction of approach. According to Table III, X_E / X_N generally lies between 0.3 and 0.8. On the assumption of Rayleigh waves certain interpretations can be made which are given in a later section.

A definite trend exists for the relationship between X_H / X_Z and period T_Z which is made clear when graphed, as in Fig. 2, where the curve shown has been drawn by eye to fit the points. In Fig. 3, similar empirical results for DeBilt are taken from Lee (6), who used monthly means. Lee's theoretical curve is also given in this figure and is derived from the theory of Rayleigh waves propagated in a system composed of granite overlain by a layer of lower velocity and density. His calculations reveal that the amplitude ratios at all periods should be generally lower when the elastic properties of the layer are closer to those of granite. Ratios of horizontal to vertical amplitudes are lower for Palisades than for DeBilt which may thus be explained by the latter being on a recent "weak" formation compared to the more compact rocks in the vicinity of Palisades. The amplitude ratios for Palisades conform to those expected from theory for such conditions.

Lee's theoretical curve, which is peaked at 5.5 sec, has been calculated on the basis of 1.6 km of clay on granite, and according to his work, would be displaced toward shorter periods for thinner surface layers. Although Palisades rests on a layer only about .5 km thick consisting of Triassic sediments with a portion of the Palisades diabase sill included, coastal plain and shelf sediments begin a few kilometers eastward from the station. These extend eastward for scores of kilometers and thicken to more than 2 km. No specific conclusions are drawn from this, however, the resemblance between the two curves suggests that the microseisms studied behave like Rayleigh waves, and that they may be used to reveal certain gross geologic features.

Weston is situated on gneisses and schists in a region of igneous and metamorphic rock whose elastic properties are presumably closer to those of granite than are those properties for the sediments and sill at Palisades. Although the Weston data are too few for graphic treatment, the X_H, X_Z ratios from Table III are considerably lower than those for Palisades, and thus also conform to Lee's theoretical results obtained from Rayleigh wave theory.

ANALYSIS OF INDIVIDUAL WAVE MOTION

From each of the microseism storms studied statistically, several one-minute intervals exhibiting regular waves identifiable on each component were selected for detailed study. It is emphasized that selection was made only on the basis of wave coherence on each of the three component records. Measurements of amplitude were made every half-second during these intervals. Particle trajectories in each of the prime planes were reconstructed by plotting trace amplitudes for both stations. No corrections were considered necessary for magnification and phase response for the Weston data. However, certain corrections should be considered for the Palisades data in view of the small differences of instrumental response. These will be considered in the discussion of the trajectories.

An example of the results for the microseism storm of October 13, 1950, and the traces from which they were derived, are shown in Fig. 4. The general appearance of the particle paths is typical of the results for each of the microseism storms studied, with similar diagrams for the other five storms being given in Fig. 5. Each sequence of orbits represents a microseism group, usually of three or four coherent wave cycles. The wave orbits have been separated to present as clear a picture of the trajectories as possible.

It is evident that the motion in the vertical planes (NS and EW) are elliptical as was derived from the preceding study of amplitude ratios, and show varying degrees of distortion. Small distortions are probably the result of background-level oscillations not apparent on the traces. Gross distortions of the ellipses have been correlated with asymmetric waves, whose distortions, although not visually apparent, are brought out in the measurements.

Although no instrumental corrections are made here, consideration of magnifications and phase differences for the Palisades components indicates that the only corrections necessary would involve a variable decrease of the vertical coordinates of the ellipses. This decrease would vary from about 25 percent for periods below 7 sec to zero at 7 sec. No significant rotation of the orbits would occur.

It is apparent that the axes of the orbital ellipses projected in the vertical planes shown, are inclined. This confirms similar conclusions derived from the preceding statistical study. Similar inclinations have been reported by many investigators for Rayleigh waves from explosions and earthquakes.

To consider the trajectories in the horizontal plane it is noted from Figs. 5 and 6 that ground motion shown here is nearly always linearly polarized. This is expected on the basis of the statistical phase differences given earlier. In Fig. 6, A on B, a striking correlation exists for the degree and direction of polarity (SE) for Palisades and Weston for the same times and same microseism storm. Instrumental corrections would cause a decrease of about 6 degrees in the angle between the north-south coordinate axis and the long axes of the orbits and a decrease in the total east-west motion by about 20 percent for Palisades. The tendency toward elliptic motion in the horizontal trajectories shown here has been observed at other stations, leading to the controversy over the type or types of seismic waves present in microseisms.

The most common interpretations for this effect have been that the observed microseisms are either combinations of Rayleigh and Love waves or of pure Rayleigh waves arriving simultaneously from different directions. The former implies that most of the time elliptic horizontal motion should exist, with pure Rayleigh or pure Love waves being observed on occasions. The latter implies that elliptic horizontal motion may be frequent, and that pure Rayleigh wave motion should be observed whenever the waves are unidirectional. Pure Rayleigh-wave type motion is common at Palisades and Weston according to the data shown here. A careful examination of the records for these microseism storms revealed only one or two cases in each one-hundred cycles in which Love wave motion was indicated by horizontal motion with no accompanying vertical motion, and such movement was always near background level and usually incoherent. Although microseisms studied at some localities seem to show a significant Love wave contribution, those reported here seem to be pure Rayleigh waves or combinations of them. Some departure from linear polarity is actually observed for accepted earthquake Rayleigh waves recorded at Palisades, and seems to be a result of interference. Further, if the source of these microseisms be considered as the obvious marine meteorologic disturbances, or from any marine effect, the sources would be generally eastward. The motions then shown in the diagrams would be retrograde and compare favorably with Rayleigh waves.

DETERMINATION OF THE DIRECTION OF WAVE APPROACH

Assuming the microseisms studied to be Rayleigh waves it is possible to apply the data and results obtained here to the determination of the directions of approach. Based on the Rayleigh wave concept, each quadrant of approach is associated with a certain set of values for the phase differences Z-E and Z-N, as is summarized in Table IV.

TABLE IV

Approach Quadrant	Z-E	Z-N
NE	90	90
SE	90	270
SW	270	270
NW	270	90

After correcting the phase differences in Table I from the calibration data and allowing for the inclinations of the elliptic axes, a dominant quadrant of approach is found for each observation. To further refine the direction, the ratio $\bar{X}_E / \bar{X}_N$ given in Table III is used to define the mean direction angle (θ=Arctan $\bar{X}E/\bar{X}N$). This is measured from north for northeast and northwest quadrants, and from south for southeast and southwest quadrants. In addition to these directions based on the statistical data, directions were also determined for the individual waves studied in the preceding section. In this case the quadrant of approach is obtained from the comparison of the particle rotation in the EW and NS vertical planes, and the direction angle, θ , is the angle between the direction of elongation of horizontal motion and the north-south coordinate axis. Such directions were determined only for the waves which showed linear polarity in the horizontal planes. Instrumental corrections were applied to these directions.

The meteorological disturbances associated with the microseisms were determined from marine weather charts, and both the azimuths of the centers,and the sectors subtended by the storms at the stations, were measured.

Table V. summarizes the direction results obtained from the statistical data, and Table VI. the results from the individual wave analysis. Northeast and southeast appear to be the only quadrants of approach which is expected for marine sources and the stations involved. In general the computed directions of approach do not coincide with the azimuths of the storm centers nor with the sectors subtended by the storms. Agreement between computed and observed directions is much better for storms that are northeast or southeast than for those directly eastward. This tendency for approach directions to be either northeast or southeast even when generating areas are to the east strongly indicates refraction of microseisms at the continental margin. In most cases when hurricanes moved from south to north off the east coast, approach directions remained to the southeast until the storm was well to the north of east. Then approach directions swing to northeast also. Strong refraction effects for earthquake Rayleigh waves were found by Press and Ewing (24) to exist for periods less than 20 seconds with indications that the effect increases for decreasing periods. Tripartite studies of Donn and Blaik (25) also indicate the existence of refraction of microseisms at continental borders. The effect of swell traveling to the coast in the wake of the storm and being responsible for this effect is negated by earlier studies (27, 28).

Of further significance in this connection is the striking tendency for east-west displacements to be lower than for north-south, as noted in Table II, especially when atmospheric storms are east of the stations. This appears to be of significance since observations reported in the literature cited earlier give horizontal amplitude ratios from 0.5 to 1.5 for other stations. Further, no approach directions from east were ever noted in this investigation. This might be explained by some propagation discontinuity, possibly structural in nature, along the continental margin. An approximate east-west orientation of the discontinuity is implied by the discrimination against microseisms from the east at stations along an approximate east-west line. Such a discontinuity would have the same trend as the continental shelf in this critical area. Amplitudes of waves from the east would be low owing to their high angle of incidence on such a discontinuity. Previous indications of this have been given by Donn (26) from microseism studies.

CONCLUSIONS

1. The dominant type of microseism ground motion at Palisades and Weston resembles that of theoretical Rayleigh waves. This is based on both a statistical and individual analysis of phase and amplitude relationships for storm microseisms recorded simultaneously on three-component seismographs. Microseisms occasionally showing elliptic rather than linear polarity in the horizontal plane are explained as being combinations of pure Rayleigh waves from different directions.

2. Geological significance of three-component microseism studies lies in possible determination of gross structural features in the vicinity of a station.

Favorable correlation between observation and theory seems to exist for such studies made at Palisades and Weston. However, those studies are not considered to be complete.

3. The use of the statistical and individual wave analysis data to determine the direction of wave approach at Palisades and Weston gives unsatisfactory results which can be explained by the existence of strong refraction of microseisms at the eastern continental border. A further implication from direction and amplitude studies is the existence of a discontinuity, possibly structural in nature, parallel to, and in the vicinity of, the continental margin.

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ACKNOWLEDGEMENTS

This research has been supported by Contract N6-onr-27133 with the Office of Naval Research, and Contract AF 19 (122) 441 with the Geophysical Research Division of the Air Force Cambridge Research Center. Father F. J. Donohue, S.J. generously made available necessary records from Weston College Observatory. Weather data was furnished by the U.S. Weather Bureau office at La Guardia Field, Long Island. Dr. Frank Press read and criticized the completed manuscript. The writers are very grateful to all of these individuals and institutions.

TABLE I. PHASE DIFFERENCE DISTRIBUTIONS
(SMOOTHED PERCENTAGE-FREQUENCIES ARE GIVEN)

PALISADES

DATE	TIME (GCT)	COMPO-NENTS	0	22½	45	67½	90	112½	135	157½	180	202½	225	247½	270	292½	315	337½	T_Z (sec)
AUG. 20 1950	1800	Z-E	3.7	4.6	5.0	5.2	5.4	6.3	8.1	9.7	10.6	9.1	8.0	5.9	5.9	5.2	4.4	3.6	5.23
		Z-N	8.1	5.7	3.4	2.7	2.7	3.1	3.3	4.2	4.8	5.8	6.6	9.6	10.2	12.2	10.9	9.9	
		N-E	6.1	4.7	4.3	3.9	4.6	5.0	5.8	6.8	8.1	8.4	8.1	7.0	7.1	6.7	7.2	6.2	
AUG. 21	0600	Z-E	2.9	5.6	7.1	9.1	11.2	14.6	15.6	14.1	9.7	5.1	2.0	0.8	0.6	0.4	0.2	1.1	4.83
		Z-N	6.8	6.1	4.9	4.6	4.1	4.4	4.8	5.9	7.0	7.7	7.9	7.6	7.8	7.0	6.9	7.7	
		N-E	7.3	6.7	5.1	3.6	2.8	4.0	5.7	7.6	7.9	7.7	7.3	7.1	6.9	6.6	6.8	7.0	
AUG. 21	1200	Z-E	3.5	5.0	7.0	8.8	10.0	11.8	13.1	13.3	10.0	5.9	2.7	2.0	1.9	1.7	1.6	2.0	4.74
		Z-N	6.6	5.6	4.4	4.2	4.1	5.0	5.6	6.4	6.7	7.0	7.1	7.0	7.2	7.6	7.9	7.7	
		N-E	9.2	7.8	5.5	3.7	3.3	3.3	5.9	7.4	8.0	7.4	5.8	4.9	5.1	6.0	7.3	8.3	
AUG. 21	1800	Z-E	1.7	3.1	4.9	7.6	12.0	16.7	18.4	16.3	9.9	4.9	2.4	1.1	1.1	0.7	0.3	0.7	4.52
		Z-N	9.8	8.8	6.7	6.1	4.3	4.1	4.8	5.0	5.2	4.7	4.7	5.0	6.1	7.3	8.7	9.9	
		N-E	6.2	6.1	5.3	5.7	6.5	8.4	9.2	10.1	8.9	7.9	5.5	4.1	2.9	3.1	4.3	5.7	
AUG. 21	2400	Z-E	2.4	4.7	7.6	10.8	14.1	16.0	16.3	13.1	7.8	3.6	1.1	0.4	0.1	0.1	0.1	0.3	4.17
		Z-N	5.6	6.2	9.2	9.2	9.8	9.3	8.6	7.1	6.1	5.7	5.1	4.6	3.4	4.0	4.3	6.0	
		N-E	10.1	9.4	8.1	6.4	8.2	7.3	4.9	5.4	5.4	5.0	4.5	3.7	4.5	5.3	7.4	9.2	
SEPT. 11	1800	Z-E	3.1	3.3	4.8	6.2	8.2	9.9	12.2	13.4	11.2	9.0	4.8	2.4	1.9	2.4	2.0	3.1	4.53
		Z-N	11.7	8.1	4.7	2.1	1.4	1.7	1.9	2.4	3.3	4.3	5.6	7.1	9.7	11.0	12.8	12.6	
		N-E	4.3	4.7	4.5	3.9	3.8	4.5	6.5	8.9	11.1	10.8	9.5	7.2	6.4	5.2	4.5	3.8	
SEPT. 11	2400	Z-E	1.1	2.9	5.2	8.7	11.8	14.4	15.6	14.7	11.9	7.2	3.7	1.3	0.8	0.3	0.1	0.3	4.98
		Z-N	8.4	6.4	4.7	4.0	4.1	4.0	3.7	4.0	4.6	6.4	6.6	7.8	8.1	9.0	9.2	9.8	
		N-E	4.1	4.4	4.7	5.9	6.1	6.8	7.0	7.1	8.4	9.4	4.3	3.1	6.4	5.2	4.0	3.8	
SEPT. 12	0600	Z-E	1.3	2.1	3.4	7.3	11.0	16.9	17.9	15.8	11.4	6.6	2.9	1.2	0.9	1.1	1.3	1.4	4.99
		Z-N	7.3	5.8	4.6	3.6	4.0	5.0	6.3	6.8	7.0	7.4	7.2	7.8	7.2	6.8	6.8	7.1	
		N-E	5.8	6.1	6.1	6.8	5.8	6.7	6.2	6.7	7.0	7.1	6.5	6.4	6.1	2.3	6.0	6.2	
SEPT. 12	1200	Z-E	4.9	7.3	10.0	12.2	12.9	11.3	10.0	8.9	8.0	5.8	2.9	0.9	0.0	0.3	1.3	3.1	5.82
		Z-N	5.8	5.6	4.9	4.9	6.7	8.9	10.0	10.0	8.9	7.6	6.9	5.5	4.4	3.3	4.0	4.2	
		N-E	6.2	4.7	4.0	4.4	5.5	7.1	10.4	8.7	7.5	6.9	6.0	5.8	5.1	5.8	6.7	7.3	
SEPT. 18 1950	0000	Z-E	3.3	4.4	5.9	8.5	13.1	12.8	12.5	10.8	8.5	6.8	2.9	2.2	2.2	2.8	2.9	3.0	4.90
		Z-N	4.5	5.9	3.4	9.9	12.3	12.8	11.7	8.8	6.4	4.1	2.7	2.0	2.0	2.7	3.0	3.9	
		N-E	3.0	2.8	3.0	3.9	5.1	7.0	9.1	12.3	13.4	12.1	8.4	5.7	4.3	3.7	3.2	2.9	
SEPT. 18	0600	Z-E	4.4	4.4	6.4	7.0	8.2	9.8	12.0	12.7	11.1	7.8	3.2	2.4	1.3	1.4	2.0	3.3	5.66
		Z-N	4.4	6.3	7.7	9.4	11.4	13.2	13.7	11.3	8.3	4.8	2.7	1.2	0.8	4.4	1.4	2.7	
		N-E	5.4	5.0	4.0	3.0	3.1	5.2	8.5	11.7	12.9	10.5	8.1	6.2	6.0	4.2	3.5	3.8	
SEPT. 18	1200	Z-E	2.3	4.7	7.3	9.9	11.4	13.0	13.2	11.8	8.7	5.6	3.9	3.0	2.2	1.2	0.8	1.0	6.05
		Z-N	4.9	5.9	8.2	10.9	13.4	13.7	12.1	9.2	6.2	3.9	2.3	1.7	1.1	1.1	2.0	3.3	
		N-E	7.9	8.2	7.2	5.7	4.6	5.1	5.8	6.6	6.7	6.2	6.9	6.7	6.0	5.9	6.1	6.6	
OCT. 13	0000	Z-E	0.0	0.8	3.4	9.6	18.0	23.2	21.8	13.4	5.4	0.8	0.0	0.0	0.0	0.0	0.0	0.0	7.70
		Z-N	1.1	3.4	9.2	16.9	22.6	20.5	13.0	5.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.4	
		N-E	18.4	21.8	17.6	10.3	4.2	1.5	0.4	0.0	0.0	0.0	0.0	0.4	1.1	1.9	4.6	10.7	
DEC. 5 1950	0000	Z-E	0.9	2.1	5.0	6.4	9.2	12.5	16.3	16.9	14.9	9.9	4.9	1.3	0.3	0.3	0.6	0.8	3.69
		Z-N	12.4	8.2	0.8	1.1	1.3	1.2	0.9	1.7	3.5	6.9	9.1	9.0	12.8	14.8	15.1	12.4	
		N-E	2.1	2.3	3.0	2.4	2.4	3.5	7.0	10.2	13.2	13.7	11.1	8.4	7.0	5.4	3.8	2.3	
DEC. 5	1200	Z-E	2.0	3.1	5.9	6.2	10.0	12.9	15.8	15.1	10.8	7.2	3.7	2.3	1.3	0.8	0.6	0.8	3.91
		Z-N	10.5	6.5	2.9	1.5	0.7	0.3	0.3	1.2	2.2	4.2	6.5	8.5	11.0	14.8	15.3	14.9	
		N-E	1.1	1.7	2.4	5.5	4.9	7.5	11.1	14.8	15.5	13.5	9.7	6.3	3.6	2.1	1.1	0.9	
SEPT. 11 1951	0000	Z-E	0.7	1.1	2.7	6.5	10.7	16.2	16.6	16.7	12.6	7.2	3.2	1.0	0.3	0.3	0.2	0.8	6.14
		Z-N	3.5	5.9	8.3	10.6	12.1	12.1	12.5	11.0	7.9	6.1	2.7	2.1	1.0	1.0	1.3	2.1	
		N-E	9.4	10.4	11.0	10.2	8.3	7.4	4.5	3.7	3.0	3.7	3.0	3.7	4.9	5.1	6.4	7.9	
SEPT. 11	0600	Z-E	0.9	2.0	4.1	7.4	11.7	15.1	16.9	15.6	12.5	7.5	3.5	1.1	0.8	0.4	0.2	0.3	6.39
		Z-N	2.2	3.5	5.7	9.5	13.1	16.1	15.9	12.7	8.9	5.0	2.5	1.0	0.5	0.4	0.8	1.4	
		N-E	11.8	11.7	9.5	7.3	5.2	5.0	4.8	4.8	4.2	3.6	3.7	3.0	3.4	4.4	7.3	10.0	
SEPT. 11	1200	Z-E	0.2	1.2	3.5	6.9	10.0	15.0	18.0	17.2	13.4	7.6	3.7	1.3	0.5	0.1	0.0	0.0	6.65
		Z-N	2.2	3.8	7.2	10.7	14.1	15.2	15.3	12.4	8.8	4.2	1.8	0.7	0.7	0.7	1.0	1.2	
		N-E	13.0	12.9	12.0	9.5	7.0	5.5	4.1	4.4	4.4	4.7	3.3	2.8	7.0	4.9	7.8	10.5	

WESTON

DATE	TIME (GCT)	COMPO-NENTS	0	22½	45	67½	90	112½	135	157½	180	202½	225	247½	270	292½	315	337½	T_Z (sec)
AUG. 21 1950	0000	Z-E	5.9	5.8	6.3	6.9	7.8	7.6	8.1	8.7	9.0	7.6	5.3	3.9	3.6	3.9	4.6	5.2	4.16
		Z-N	5.2	2.6	1.1	0.7	0.7	0.4	0.3	0.8	2.8	6.2	13.1	14.9	16.9	15.3	12.4	8.6	
		N-E	5.6	4.7	4.4	4.4	4.7	5.1	6.6	7.7	9.8	9.1	8.6	6.4	6.0	5.7	6.0	6.1	
AUG. 21	0600	Z-E	4.8	8.3	11.4	13.4	13.6	12.4	10.4	7.9	5.0	2.8	1.4	1.0	0.9	1.2	1.7	2.7	3.82
		Z-N	4.7	2.2	1.7	1.4	1.0	0.6	0.8	2.0	4.6	6.9	9.9	11.9	14.7	15.2	13.6	8.9	
		N-E	3.1	3.4	4.3	5.6	6.3	7.3	9.2	11.9	13.0	11.2	7.4	4.4	3.2	3.1	3.2	3.1	
AUG. 21	1200	Z-E	4.2	5.8	7.3	9.8	14.0	13.6	12.6	9.9	7.0	3.2	2.1	1.4	2.1	2.6	2.9	2.3	4.28
		Z-N	6.2	4.0	2.3	1.4	1.1	1.4	2.1	4.3	7.1	10.1	11.2	11.3	10.4	9.8	9.3	7.9	
		N-E	5.4	5.1	4.8	4.6	5.2	6.0	7.9	8.9	9.4	8.1	6.6	5.6	5.4	5.8	5.7	5.7	
AUG. 21	1800	Z-E	4.1	7.9	12.6	15.3	16.4	14.3	10.8	7.4	4.8	2.7	1.1	0.2	0.0	0.0	0.4	1.4	4.27
		Z-N	5.4	3.4	2.4	1.6	1.2	1.3	1.8	2.2	5.0	7.7	9.8	12.1	13.2	12.9	10.9	7.8	
		N-E	3.7	3.7	3.9	4.1	5.0	6.3	9.3	12.0	15.0	11.6	8.3	5.2	3.9	3.4	3.4	3.6	
AUG. 21	2400	Z-E	3.7	7.1	10.2	13.4	15.3	15.7	13.7	9.4	5.4	2.3	1.1	0.3	0.1	0.1	0.4	1.7	3.91
		Z-N	7.3	5.1	3.2	2.4	2.3	2.1	2.4	2.8	3.8	5.0	7.3	10.1	11.9	13.2	11.3	10.1	
		N-E	5.0	3.3	5.2	5.3	5.7	6.7	8.3	9.8	10.0	8.7	6.4	5.7	4.7	4.2	4.0	4.6	

TABLE II.

Summary of frequency of occurrence, n, of phase differences

Palisades

Phase Dif.	0	22½	45	67½	90	112½	135	157½	180	202½	225	247½	270	292½	315	337½	360
Component																	
Z-E	0	0	0	0	2	2	9	4	1	0	0	0	0	0	0	0	0
Z-N	0	0	0	0	3	3	3	0	0	0	1	1	0	1	4	2	0
N-E	3	3	1	0	0	0	1	1	5	4	0	0	0	0	0	0	0

Weston

Phase Dif.	0	22½	45	67½	90	112½	135	157½	180	202½	225	247½	270	292½	315	337½	360
Component																	
Z-E	0	0	0	1	1	2	0	0	1	0	0	0	0	0	0	0	0
Z-N	0	0	0	0	0	0	0	0	0	0	0	1	2	2	0	0	0
N-E	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0

TABLE III. AMPLITUDE DATA

PALISADES

Date	GCT	Ground Amplitude (micron) $\bar{A}_E$	$\bar{A}_N$	$\bar{A}_Z$	Amplitude Ratio $\bar{A}_E/\bar{A}_Z$	$\bar{A}_H/\bar{A}_Z$	Period $\bar{T}_Z$
Aug 20, 1950	1800	1.62	1.93	2.95	0.55	1.74	5.23
Aug 21	0600	4.01	5.16	5.78	0.69	1.36	4.83
	1200	3.01	3.46	4.45	0.68	1.39	4.74
	1800	3.33	4.31	4.62	0.72	1.32	4.52
	2400	2.34	2.92	3.39	0.69	1.41	4.17
Sept 11,1950	1800	2.75	3.29	4.55	0.60	1.62	4.53
	2400	4.75	6.38	7.11	0.67	1.34	4.98
Sept 12,1950	0600	6.51	8.28	9.62	0.68	1.40	4.99
	1200	6.71	9.09	11.36	0.59	1.45	5.82
Sept 18,1950	0000	1.75	1.61	2.44	0.72	1.87	4.90
	0600	2.21	2.37	3.43	0.64	1.72	5.55
	1200	2.94	3.50	4.08	0.72	1.44	6.05
Oct 13,1950	0000	1.73	2.56	2.28	0.68	1.12	7.70
Dec 5,1950	0900	4.00	6.45	7.93	0.50	1.38	3.63
	1200	4.30	6.83	7.84	0.55	1.31	3.91
Sept 11,1951	0000	1.52	2.28	2.24	0.68	1.19	6.14
	0600	1.90	2.75	2.71	0.70	1.20	6.39
	1200	2.00	3.01	2.81	0.71	1.14	6.65

WESTON

Date	GCT	(Trace Amplitude-mm) $\bar{A}_E$	$\bar{A}_N$	$\bar{A}_Z$	$\bar{A}_E/\bar{A}_Z$	$\bar{A}_H/\bar{A}_Z$	$\bar{T}_Z$
Aug 20,1950	2400	2.34	4.50	3.45	0.68	0.93	4.16
Aug 21	0600	5.03	9.83	6.88	0.73	0.87	3.82
	1200	5.06	9.06	6.17	0.82	0.88	4.28
	1800	5.16	10.44	6.32	0.82	0.78	4.27
	2400	4.02	7.36	4.79	0.84	0.85	3.91

TABLE V. COMPARISON OF COMPUTED DOMINANT APPROACH DIRECTIONS WITH OBSERVED STORM DIRECTIONS

PALISADES

Date	GCT	Dominant Quadrant	Refined Direction For $\theta = \bar{\lambda}_E/\bar{\lambda}_W$	Direction of Storm Center	Angle subtended at Station by Storm
			degrees	degrees	degrees
Aug 20,1950	1800	SE	S29E	S37E	74
Aug 21	0600	SE	S35E	S87E	76
	1200	SE	S34E	N67E	67
	1800	SE	S36E	N52E	38
	2400	NE	N35E	N57E	31
Sept 11,1950	1800	SE	S31E	S38E	103
	2400	SE	S34E	S73E	114
Sept 12	0600	SE	S34E	S76E	99
	1200	SE	S31E	S79E	86
Sept 18,1950	0000	NE	N36E	N42E	33
	0600	NE	N33E	N43E	25
	1200	NE	N36E	N44E	22
Oct 13,1950	0000	NE	N34E	N62E	30
Dec 5,1950	0900	SE	S27E	S86E	115
	1200	SE	S29E	N77E	99
Sept 11,1951	0000	NE	N34E	N71E	34
	0600	NE	N35E	N65E	27
	1200	NE	N35E	N61E	29

WESTON

Date	GCT	Dominant Quadrant	Refined Direction For $\theta = \bar{\lambda}_E/\bar{\lambda}_W$	Direction of Storm Center	Angle subtended at Station by Storm
Aug 20,1950	2400	SE	S34E	S27E	98
Aug 21	0600	SE	S36E	S72E	102
	1200	SE	S39E	N72E	90
	1800	SE	S39E	N65E	59
	2400	SE	S40E	N57E	38

TABLE VI. COMPARISON OF COMPUTED INDIVIDUAL WAVE APPROACH DIRECTIONS WITH OBSERVED STORM DIRECTIONS

PALISADES

Date	GCT	Individual Wave Approach Directions degrees	Direction of Storm Center degrees	Angle subtended at Station by Storm degrees
Aug 21,1950	1801	S34E,S36E,S44E	N62E	38
Sept 11,1950	1925	S15E,S6E,S2E	S38E	103
Sept 18,1950	1150	N35E,N26E	N44E	22
Oct 13,1950	0033	N36E,N28E	N62E	30
Dec 5,1950	1817	S20W,S21E	N77E	99
Sept 11,1951	1207	N69E,N62E,N42E,N39E	N61E	29

WESTON

Date	GCT	Individual Wave Approach Directions degrees	Direction of Storm Center degrees	Angle subtended at Station by Storm degrees
Aug 21,1950	1759	S27E,S18E,S19E,S12E	N65E	59

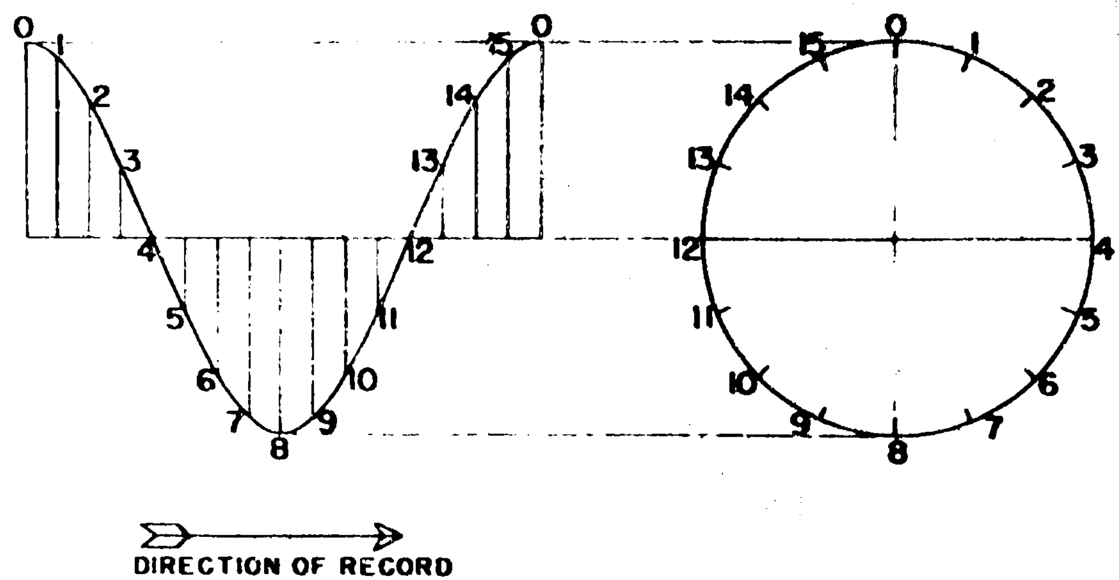

Fig. 1. Method of phase measurements used on the seismograms.
(After A. W. Lee)

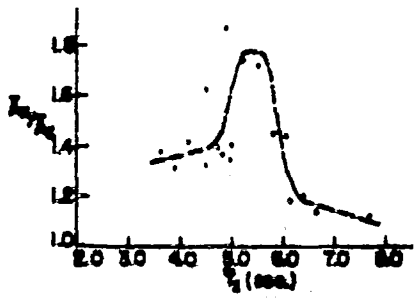

Fig. 2. Empirical curve of the ratio of the mean horizontal to the mean vertical amplitudes plotted against mean period.

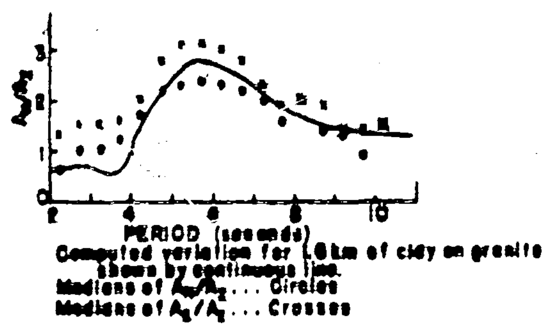

Fig. 3. A. W. Lee's observed and theoretical data for amplitude ratios and period.

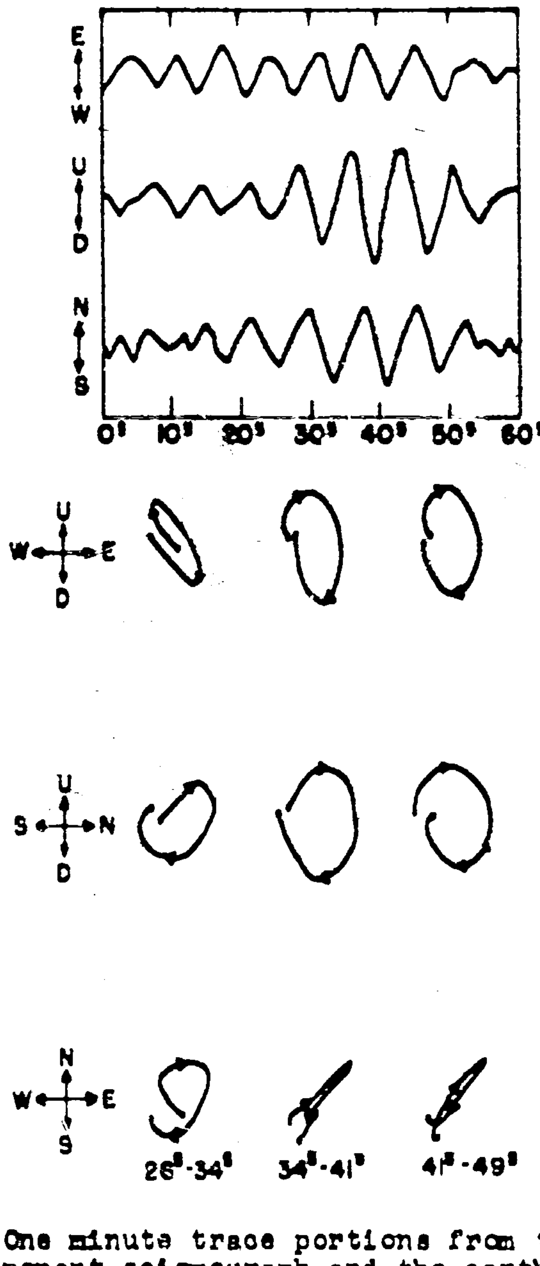

Fig. 4. One minute trace portions from the Palisades three-component seismograph and the earth-particle trajectories for the three principal waves at 26 to 49 sec. on October 13, 1950, 0030GCT.

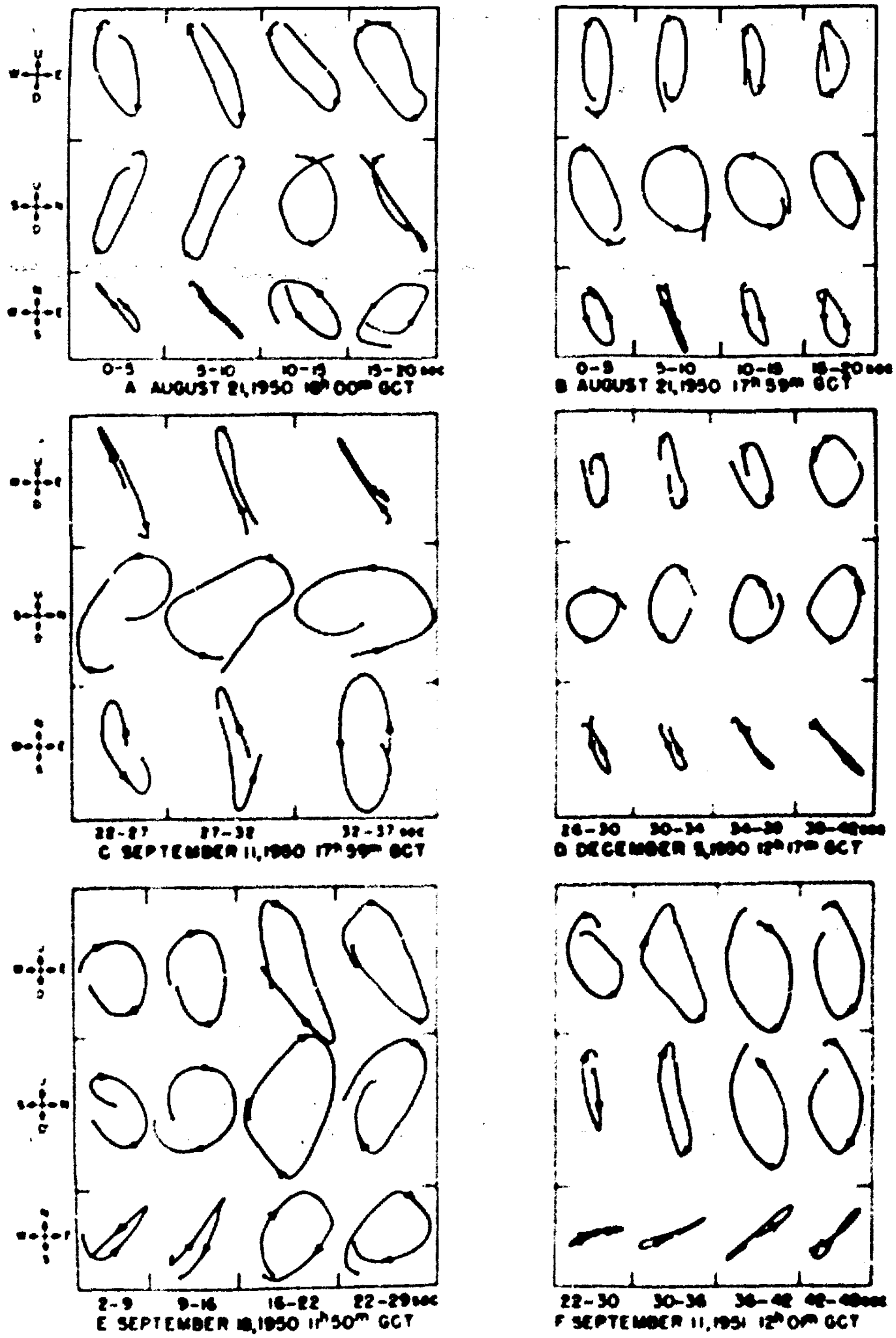

Fig. 5. Earth particle trajectories for selected microseisms from five microseism storms. A,B,C,D, and F are for Palisades and E, for Weston. (Note that A and B are for the same time.)